3.8 Meteorological risk: extreme temperatures

Glenn McGregor, *Angie Bone, Florian Pappenberger*

3.8.1 Temperature extremes in a disaster risk management context

Understanding temperature extremes in a DRM context involves getting to know how often temperature extremes occur, the conditions under which they occur and establishing associated direct and indirect societal impacts.

Knowledge about temperature extremes can inform the development of strategies for managing the risk associated with this type of natural event. That temperature extremes do result in disastrous consequences, in terms of lives lost, is manifest via the observed impacts of a range of extreme temperature events over the last few decades (Table 3.3). Noteworthy is that all top 10 disasters are related to extreme high as opposed to low temperatures.

Temperature extremes, although rare, are important from a DRM perspective as they can lead to a range of substantive direct and indirect impacts on human activity and other systems.

3.8.2 What are temperature extremes?

Temperature extremes can occur over a range of temporal (e.g. daily, monthly, seasonal, annual, decadal) and geographical scales (e.g. local to regional to global). They are usually defined in terms of their position in a distribution of observed temperature values or as a threshold value recorded at a meteorological or climate station.

Temperature extremes can be expressed as a probability of occurrence, or as a return period (e.g. 5 % probability or 1 in 20 year return period). Occasionally, the term 'return period' is misinterpreted to mean an event of a particular magnitude, so that an event with a return period of 1 in 20 years, having once occurred, will occur again only after 20 years have passed. This is incorrect, as at any one time the occurrence of a particular temperature will have a specific probability associated with it. Given this, it is entirely possible to have two 1 in 20 year events in successive years or indeed in the same year.

A threshold value will be a specific high or low temperature value, above or below which there is a discernible impact. These can be described in terms of percentiles, for example, the 5^{th} or 95^{th} percentile, meaning that for all the temperature observations recorded for a location, the highest or lowest set of temperatures are considered to fall within the lowest or highest 5 % of values. Percentiles are a relative measure of extreme values, as the value associated with a particular percentile will vary from location to location. For example, the 95th percentile value of temperature for a location in southern Europe may be 35°C, while for a northern European location it may be 28°C.

Probabilities, return periods and percentiles are just a few of a wide range of possible measures of temperatures extremes. For example, Table 3.4 lists a set of measures of temperature extremes considered relevant to a range of sectors of the economy and society (Donat et al., 2013). Among these are some that refer to the duration of high or low temperatures over several days. These are often referred to as heat waves or cold waves. Although these terms are applied extensively in a range of fora, there is no standard definition of what a heat wave or cold wave is, despite a number of attempts to develop 'universal' heat wave and cold wave definitions (Allen and Sheridan, 2016; Lhotka and Kysely, 2015; Perkins and Alexander, 2013; Robinson, 2001; Tong et al., 2010).

Building a picture of the nature of temperature extremes for a particular location or region is dependent on measurements from daily weather and climate observing stations. Accordingly, a number of daily temperature datasets that can be used for risk analysis have been constructed based on available station data (Klok and Tank, 2009; Menne et al., 2012).

There is a range of temperature extreme metrics. Statistical measures including probabilities, return periods and percentiles can be used to describe their occurrence. Knowledge gaps exist concerning extreme urban temperatures.

TABLE 3.3

Top 10 extreme temperature disasters and associated death toll by country and date.
Source: EM-DAT (2009)

Country	Disaster type	Date	Total number of deaths
Russian Federation	Extreme high temperature	01/06/2010	55 736
Italy	Extreme high temperature	16/07/2003	20 089
France	Extreme high temperature	01/08/2003	19 490
Spain	Extreme high temperature	01/08/2003	15 090
Germany	Extreme high temperature	01/08/2003	9 355
France	Extreme high temperature	29/06/2015	3 275
Portugal	Extreme high temperature	01/08/2003	2 696
India	Extreme high temperature	26/05/1998	2 541
India	Extreme high temperature	20/05/2015	2 248

In addition to observational data, other sources are increasingly being used to develop extreme temperature climatologies (e.g. assembled via data rescue and reconstruction projects, as well as the analysis of diaries and other historical documents (McGregor, 2015)). Considerable effort has also gone into constructing gridded temperature datasets with a variety of spatial and temporal resolutions (Donat et al., 2013). In the case of data-sparse regions, stochastic weather generators have also been applied to the analysis of temperature extremes (Rahmani et al., 2016; Steinschneider and Brown, 2013; Wilks, 2012). A range of reanalysis products such as the 20th century (100-year) reanalysis dataset produced by the ECMWF (ERA-20C, n.d.) also offer considerable potential for extreme temperature analyses. Because weather and climate stations were originally located to be representative of atmospheric processes over large regions, there are very few long-term urban weather stations. This has constrained the development of a full understanding of the complexities of urban temperature fields and associated extremes (Chen et al., 2012).

Accordingly, attention is now being turned to the development of urban climate networks and information systems (Chapman et al., 2015; Choi et al., 2013; Honjo et al., 2015; Hu et al., 2016; Muller et al., 2013a, b). Furthermore, satellite-based high spatial

TABLE 3.4

List of the temperature indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) and calculated based on Global Historical Climatology Network (GHCN)-Daily station data. Percentile values used as the threshold for some of the indices are calculated for the base period 1961-90.
Source: adopted from Donat et al. (2013)

Identifier	Indicator name	Indicator definition	Units
TXx	Hottest day	Monthly maximum value of daily maximum temperature	°C
TNx	Warmest night	Monthly maximum value of daily minimum temperature	°C
TXn	Coldest day	Monthly minimum value of daily maximum temperature	°C
TNn	Coldest night	Monthly minimum value of daily minimum temperature	°C
TN10p	Cool nights	Percentage of time when daily minimum temperature < 10th percentile	%
TX10p	Cool days	Percentage of time when daily maximum temperature < 10th percentile	%
TN90p	Warm nights	Percentage of time when daily minimum temperature > 90th percentile	%
TX90p	Warm days	Percentage of time when daily maximum temperature > 90th percentile	%
DTR	Diurnal temperature range	Monthly mean difference between daily maximum and minimum temperature	°C
GSL	Growing season length	Annual (1 January to 31 December in NH, 1 July to 30 June in SH) count between first span of at least 6 days with TG > 5°C and first span after 1 July (1 January in SH) of 6 days with TG < 5°C. (NH stands for Northern Hemisphere, SH for Southern Hemisphere and TG is daily mean temperature)	Days
ID	Ice days	Annual count when daily maximum temperature < 0°C	Days
FD	Frost days	Annual count when daily minimum temperature < 0°C	Days
SU	Summer days	Annual count when daily maximum temperature > 25°C	Days
TR	Tropical nights	Annual count when daily minimum temperature > 20°C	Days
WSDI	Warm spell duration index	Annual count when at least 6 consecutive days of maximum temperature > 90th percentile	Days
CSDI	Cold spell duration index	Annual count when at least 6 consecutive days of minimum temperature < 10th percentile	Days

resolution surface temperature observations are also being applied in the analysis of urban surface temperature fields (Azevedo et al., 2016; Hu et al., 2015; Jin, 2012) as well as the output from urban climate numerical models (Best and Grimmond, 2015; Loridan and Grimmond, 2012).

3.8.3 Climatic variability and change and temperature extremes

Climatic variability refers to variations in climate conditions from time period to time period (e.g. intra-seasonal, inter-annual, inter-decadal). In general, climatic variability is connected with variations in the state of the atmospheric and ocean circulation and land surface properties (e.g. soil moisture) at the intra-seasonal to inter-decadal timescales. Climate change in contrast refers to a systematic change in the statistical properties of climate (e.g. mean and standard deviation, etc.) over a prolonged period (e.g. several centuries) as manifested by an upward or downward trend in, for example, extreme temperature values. For the majority of the Earth's climate history, systematic changes in climate have occurred because of natural causes, such as variations in the nature of the Earth's orbit around the sun or solar output. However, there is now mounting evidence that humans are an important climate agent.

Weather experienced at the surface of the Earth is very much influenced by the atmospheric circulation and the pattern of air and moisture flow above a location or region. Many extreme temperature events can therefore be explained in terms of unusual patterns of atmospheric circulation, such as 'blocking', which the term given to a situation in which a high-pressure system becomes 'stuck' and does not move for several days. Blocking results in the flow of either very warm or cold air over a region or cloudless skies that enhance heat gain or heat loss from the Earth's surface. For example, Della-Marta et al. (2007) have shown that heat waves over Europe are related to persistent and large-scale high-pressure systems.

Unusual atmospheric circulation patterns, which are often related to major modes of climatic variability, spawn extreme temperature events. There is mounting evidence that human-related climate change is affecting extreme temperature occurrence.

Alterations to the usual pattern of atmospheric circulation and thus the occurrence of blocking and associated extreme temperature events can often be traced back to interactions between the ocean and atmosphere or modes of climatic variability, such as the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Donat et al., 2014; Hoy et al., 2013; Scaife et al., 2008). For example, there is evidence that extreme maximum temperatures can be significantly influenced by ENSO for a range of regions across the world (Arblaster and Alexander, 2012; Kenyon and Hegerl, 2008; Parker et al., 2014) as well as by Madden–Julian Oscillation-related anomalies in tropical convection (Cassou et al., 2005; Matsueda and Takaya, 2015). Similarly, the NAO has been found to influence the occurrence of both high- and low-temperature extremes across Europe (Burgess and Klingman, 2015; Hoy et al., 2013; Kenyon and Hegerl, 2008; Moore and Renfrew, 2012; Scaiffe et al., 2008). Changes in the position of the Inter-Tropic Convergence Zone also seem to alter the possibility of temperature extremes in France and Egypt (Boe et al., 2010).

The IPCC has concluded that there is unequivocal evidence that humans, through a range of activities and an intensification of the greenhouse effect, are having an impact on the Earth's climate (IPCC, 2013). This is most evident through an increase of the global mean temperature of about 0.8°C since 1880, with two-thirds of that increase occurring since 1975, at a rate of roughly 0.15-0.20°C per decade (NASA, 2016). Understandably, this observed increase and that projected for the next several decades has implications for the occurrence of high- and low-temperature extremes (Russo et al., 2014; Seneviratne et al., 2012). That changing global temperatures appear to be already manifesting themselves in an altered occurrence of temperature extremes and heat and cold waves are evident at a range of geographical scales (Fischer, 2014; Schar, 2016). Furthermore, there is emerging evidence that a number of recent extreme temperature events are in part attributable to human-related changes in global temperatures (Easterling et al., 2016, Kim et al., 2015; Mitchell et al., 2016).

3.8.4 Health impacts of temperature extremes

Both high and low temperatures, indoors and outdoors, pose substantial risks to human health, including increases in mortality, morbidity and health service use (Ryti et al., 2016; WMO, 2015). In many countries, the health impacts of cold temperatures substantially outweigh those of heat (Gasparrini et al., 2015).

The scale and nature of the health impacts observed depends on the timing, intensity and duration of the temperature event, the level of acclimatisation and adaptation of the local population, infrastructure and institutions to the prevailing climate, as well as the definitions and methodologies used for scientific research. As such, the health effects of temperature extremes and the determinants of vulnerability are, to some extent, context specific.

Population health impacts start to be observed at winter and summer temperatures that are considered moderate for the season and then increase as temperatures become more extreme, in what is variously described as a U-, V- or J-shaped curve. The precise threshold temperatures for health impacts vary by region and country, as does the scale of the health impacts by degree change in temperature, but the overall pattern remains similar wherever it has been studied.

For both heat and cold, the impact of temperature is more marked for deaths than for hospitalisations (Hajat et al., 2016; Linares and Diaz, 2008); this may suggest that individuals die before they reach health care. Temperature extremes may also result in illness that is not sufficiently severe to require hospital attention and that has not been captured by these studies.

For heat, deaths and hospitalisations occur extremely rapidly (same day) and they may be followed by a degree of impact displacement (health impacts in the frail brought forward), which returns to normal within a matter of days (Basu, 2009). The onset of health impacts for cold are slower and persist for longer (up to 4 weeks), with short-term displacement effects not apparent (Analitis et al., 2008).

The health impacts of temperature extremes, which can be direct or indirect, are moderated by a range of social determinants, which can be broadly referred to as vulnerability and resilience.

Longer heat events are associated with greater health effects because of the longer period of exposure (D'Ippoliti et al., 2010), but this has not been consistently observed for cold (Ryti et al., 2016).

Severe heat events that occur towards the beginning of a season have greater health impacts; this is likely to be partly due to loss of the most vulnerable members of the population during the first episode and partly due to population adaptation for subsequent events (Baccini et al., 2008). This pattern is less clear for severe cold, with some authors indicating that cold weather events towards the end of the season are associated with greater mortality (Montero et al., 2010a).

There is some evidence that there has been a reduction in health effects from heat extremes over recent years in some countries, which suggests that there has been some individual and institutional adaptation (Arbuthnott et al., 2016). This is less well established for cold risks.

3.8.4.1 Health impacts

Health impacts may be direct (caused by the direct effect of the hazard) or indirect (caused by the consequences of the hazard such as changes in behaviour or impact on services), as shown in detail in Table 3.5.

a) Direct impacts

As the ambient temperature changes, the human body's physiology adapts in order to maintain a stable body temperature. This includes changes to the circulatory, respiratory and nervous systems to allow cooling or to protect vital organs (Ryti et al., 2016; WMO, 2015).

Direct health impacts occur when a stable body temperature cannot be

TABLE 3.5

Direct and indirect health impacts of temperature extremes

Health impacts	Heat	Cold
Direct	Increased risk of classical heat illness: • dehydration • heat cramps • heat exhaustion • heat stroke Increased risk of death from: • respiratory disease • cardiovascular disease • other chronic disease (e.g. mental health conditions and renal disease) Increased risk of hospitalisation particularly from: • respiratory disease • diabetes mellitus • renal disease • stroke • mental health conditions Increased risk of poor outcomes in pregnancy	Increased risk of classical cold illness: • hypothermia • frostbite Increased risk of death from: • cardiovascular disease • respiratory disease • other chronic diseases (e.g. stroke and dementia) Increased risk of hospitalisation particularly from: • respiratory disease • cardiovascular disease • stroke Increased risk of poor outcomes in pregnancyy
Indirect	Impact on health services including: • increased ambulance call-outs and slower • response times • increased numbers of emergency department attendances • increased number of hospital admissions • storage of medicines Increased risk of accidents: • drowning • work-related accidents • injuries and poisonings Increased risk of: • outbreaks of gastrointestinal disease • marine algal blooms Potential disruption to infrastructure: • power • water • transport • productivity	Impact on health services including: • increased ambulance call-outs and slower response times • increased numbers of emergency department attendances • increased number of hospital admissions Increased risk of accidents: • injuries from falls • traffic accidents • carbon monoxide poisonings Increased risk of: • outbreaks of gastrointestinal disease • social isolation Potential disruption to infrastructure: • power • water • transport

maintained (e.g. when temperatures are too extreme), when clothing or shelter is not suitable or when physiological responses are impaired (e.g. through disease, normal ageing or using certain medications). Moreover, these impacts may be exacerbated when other demands are placed on the body, such as strenuous activity or drug/alcohol use. This produces classical temperature-related disease, such as hypothermia and heat stroke, both of which may have a rapid onset, may not be quickly identified and may be fatal.

However, classical hypothermia and heat stroke are not the major cause of health impacts from temperature extremes; most temperature-related deaths and illness are from chronic diseases such as heart and lung disease (Bunker et al., 2016), which form an important proportion of the background disease burden in European populations. This is because an already impaired physiological system is less able to adapt to the ambient temperature, and the physiological changes needed to regulate temperature may worsen pre-existing disease.

b) Indirect impacts

Temperature extremes also have indirect impacts on health, for example through impacts on services or changes in individual behaviour as a result of the temperature.

The impact on health services may be mediated through increasing demand for care, direct and indirect impacts on staff, which affect their ability to work, or ambulance response times (Thornes et al., 2014). Temperatures extremes may have impacts on wider infrastructure that is essential for health, such as power, water and transport (USAID, 2013).

Behavioural changes may have inadvertent negative health consequences, replacing one risk with another, which is an important explanation for the increase in injuries associated with hot and cold weather (Bulajic-Kopjar, 2000; Otte et al., 2016).

3.8.4.2 Determinants of vulnerability

The major determinants of vulnerability of a population to temperature extremes relate to the features of the population exposed and their capacity to respond and adapt to the temperature conditions over long and short time frames. Determinants of vulnerability can be broadly categorised by demographic, health, physical, socioeconomic and institutional factors, many of which are inter-related and dynamic.

Temperature extremes rarely occur in isolation and related hazards such as snow/ice, drought/wildfires, poor air quality or other unrelated disasters may coincide in time and geography. Responses to these additional hazards may alter existing vulnerabilities and the capacity to adapt to temperature extremes.

a) Demographic determinants

The physiology of older people and the very young renders them more vulnerable to temperature extremes. They may also be less able to adapt their behaviours or environmental conditions and may be more dependent on others (Collins, 1986; Hansen et al., 2011). New migrants or tourists may not understand warnings or how to seek help. Some studies have suggested increased risk by gender (female) and race (black and minority ethnic groups) but this may be explained by alternative factors such as age, income, education, underlying disease and access to health care.

b) Health status determinants

Many physical and mental health conditions increase vulnerability to adverse temperatures through a direct effect on the body's physiology or through the effect of certain medications (Hajat et al., 2007). People with poor health or disability may be less aware of warnings, may be less able to adapt their behaviours or environmental conditions, and may be more dependent on others.

c) Physical determinants

People spend approximately 80 % of their time indoors, with the elderly or unwell spending longer periods indoors. Buildings (including homes, hospitals, schools and prisons) are not always adapted for temperature extremes and may have insufficient heating/energy efficiency or cooling measures (Conlon et al., 2011; Hansen et al., 2011).

People who have inadequate shelter (e.g. displaced or homeless populations) might be particularly exposed to temperature extremes and often have associated vulnerabilities such as poor health or economic circumstances.

d) Socioeconomic determinants

People who are socially isolated are more at risk from temperature extremes because they are less able to access community support, and may also have additional health or other vulnerabilities (Bouchama et al., 2007; Tod et al., 2012).

Low-income groups may be less able to adapt to their behaviours or environment. Certain occupational groups, such as labourers, may not always be afforded adequate protection from temperature extremes (e.g. undertaking strenuous physical work during very hot periods) (Hanna et al., 2011).

e) Behavioural/cultural determinants

When temperatures become more extreme, most people take some action to adapt to the conditions. However, some factors limit the ability to adapt, such as age, poor health or economic circumstances, and certain belief or value systems may also mean that appropriate action is not taken in response to the temperature conditions (Hansen et al., 2011; Tod et al., 2012). Certain behaviours, intended to be protective, may inadvertently increase health risks (e.g. swimming in unsupervised open waters (Fralick et al., 2013), shovelling snow (Franklin et al., 1996) or using unsafe heating appliances (Ghosh et al., 2016)).

f) Institutional determinants

Health services need robust plans in order to manage the potential disruption and increased demand during and following temperature extremes; their ability to respond influences population vulnerability. This also applies to supporting infrastructure such as power, water, communication and transport systems. Mass gatherings can place additional strains on services, especially if they coincide with temperature extremes (Soomaroo and Murray, 2012).

Employers should take action to ensure that employees are able to take necessary protective actions, such as increasing fluid intake, having access to adequate rest and shade and restricting strenuous activity to cooler parts of the day.

Many countries have formal plans and policies that promote actions to reduce the risk of temperature extremes, such as the Heatwave and Cold Weather Plans for England (see Chapter 3.8.6.2).

3.8.5 Other impacts of temperature extremes

To date, the human health impacts of high and low temperatures have received a great deal of attention in both the academic and technical literature related to DRM compared with 'other' impacts. In general, 'other' direct and indirect impacts tend to be less well understood than those related to human health. This, however, does not make them less important, as heat- or cold-related impacts may lead to complex disasters, for example those that may arise from the malfunction of energy supply systems, which may lead to the failure of the critical infrastructure necessary to maintain a range of human activity systems and, most importantly, the emergency services. A summary of other impacts arising from low- and high-temperature extremes is given below:

It has been documented that both high and low temperatures have significant effects on plants (Barlow et al., 2015).

Extreme heat stress can reduce plant photosynthetic and transpiration efficiencies and negatively impact plant root development, which acts collectively to reduce the yield of crops. In general, extreme high temperatures during the reproductive stage will affect pollen viability, fertilisation and grain or fruit formation (Hatfield and Prueger, 2015).

Late frosts are particularly damaging to the opening buds of plants. More economic losses in the United States are caused by crops freezing than by any other weather hazard (Snyder and Melo-Abreu, 2005). Even a single night with unusually low temperatures can lead to significant ecological and economic damage (Inouye, 2000). Because of climate change, many plants are now coming out of winter dormancy earlier (Walther et al., 2002), which leaves them even more susceptible to frost damage. Frosts can have lasting effects, as they can cause local extinctions and influence the geographical distribution of some species (Inouye, 2000).

Livestock, such as rabbits, pigs and poultry, are vulnerable to extreme temperatures. Milk production and cattle reproduction decreases during heat waves, and millions of birds have been lost as a result of such events. In extreme cold weather, livestock are also at risk if not protected from the cold (Adams, 1997).

It is a concern that non-health impacts of temperature extremes are not entirely understood, as in combination they possess the potential to create complex disasters and, thus, to have far-reaching societal impacts.

Air quality is impacted by both heat waves and low-temperature events. Increased ozone pollution is associated with high temperatures, and nitrogen oxides, SO2 and particulate matter pollution is associated with low temperatures (Hou and Wu, 2016). Heat waves also affect water quality, bringing an increased risk of algal blooms, causing the death of fish in rivers and lakes and the death of other organisms in the water ecosystem (Adams, 1997).

Heat waves can directly impact ecosystems by constraining carbon and nitrogen cycling and reducing water availability, with the result of potentially decreasing production or even causing species mortality. Extreme temperature conditions can shift forest ecosystems from being a net carbon sink to being a net carbon source (IPCC, 2012).

The effects of both high and low temperatures can be exacerbated if combined with water shortages, leading to drought (for a detailed discussion, see Chapter 3.9).

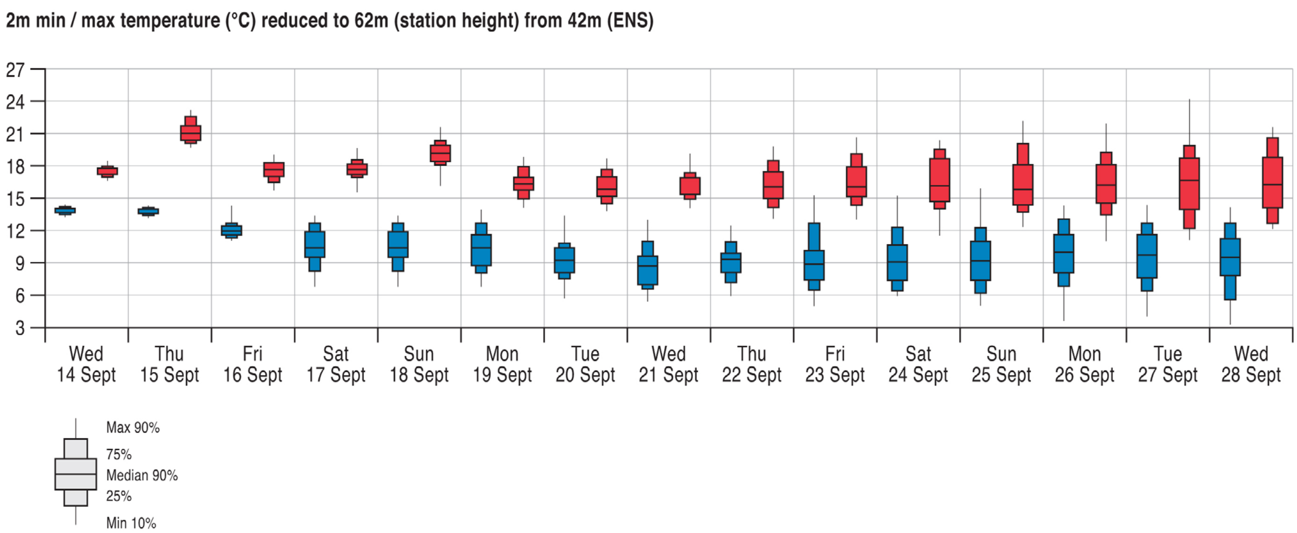
3.8.6 Managing temperature extremes

3.8.6.1 Forecasting

Forecasting extreme temperatures on the medium (more than 3 days) to seasonal (up to 6 month) scale is an important tool for civil protection

FIGURE 3.29

Ensemble forecast for maximum and minimum temperature in Durham, United Kingdom, issued on 14/09/2016, 00 UTC (Coordinated Universal Time). The figure illustrates the maximum and minimum daily temperature for each day, shown as a box plot, giving a range of possible maximum and minimum temperatures and, therefore, the uncertainty in the forecast; the further ahead a forecast is issued, the more uncertain it becomes.
Source: courtesy of authors



(Mayes, 2012; Ilkka et al., 2012).

However, forecasts on this timescale are uncertain and, therefore, multiple scenarios, known as ensembles, are used. Figure 3.29 shows such a forecast for 15 days for the city of Durham (United Kingdom). This plot clearly shows that the further ahead a forecast is issued, the more uncertain it becomes, with a range of possible values. This poses a challenge for forecasting heat and cold waves beyond the medium timescale.

Heat and cold wave predictability is also linked to a forecast model's ability to predict transitions between circulation patterns such as blocking and phases of modes of climatic variability such as ENSO and the NAO, as described in Chapter 3.8.3. Because of their low-frequency nature and their teleconnections, modes of climatic variability can exhibit predictability on the subseasonal timescale. A further source of predictability also arises from the effect of soil moisture conditions in the amplification of the temperature anomalies (Quesada et al., 2012). Therefore, accurate skill in predicting persistent large-scale high-pressure systems is fundamental to forecasting heat and cold waves.

The ideal method by which to eval-

FIGURE 3.30

2-metre temperature composites from ERA-Interim weekly mean anomalies for heat wave events: western Europe (left), northern Europe (centre) and Russia (right).
Source: courtesy of authors

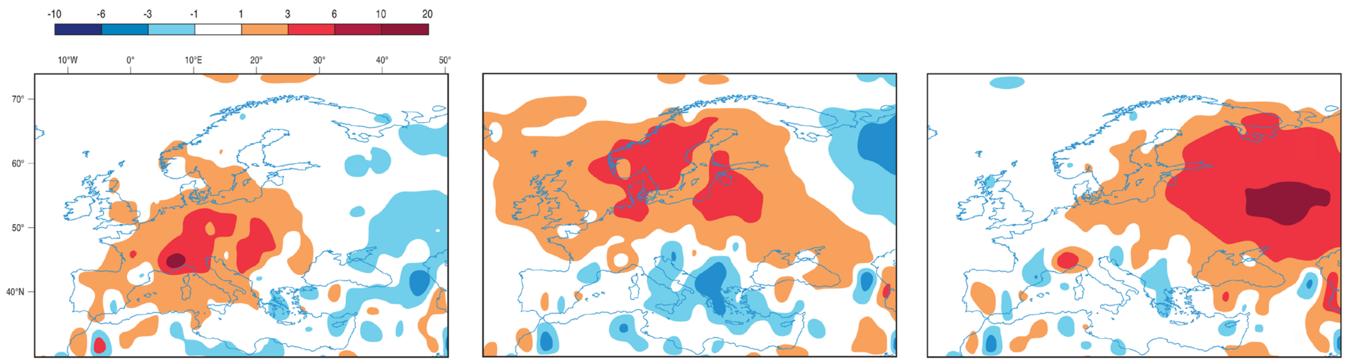
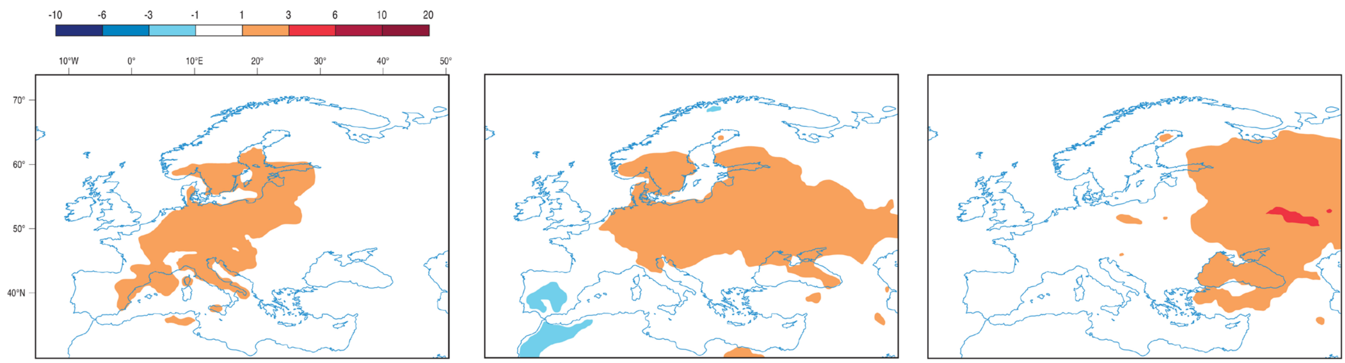


FIGURE 3.31

2-metre temperature composites from the ensembles forecast at 12-18 days verifying the same events as in Figure 3.30. Western Europe (left), northern Europe (centre) and Russia (right).
Source: courtesy of authors

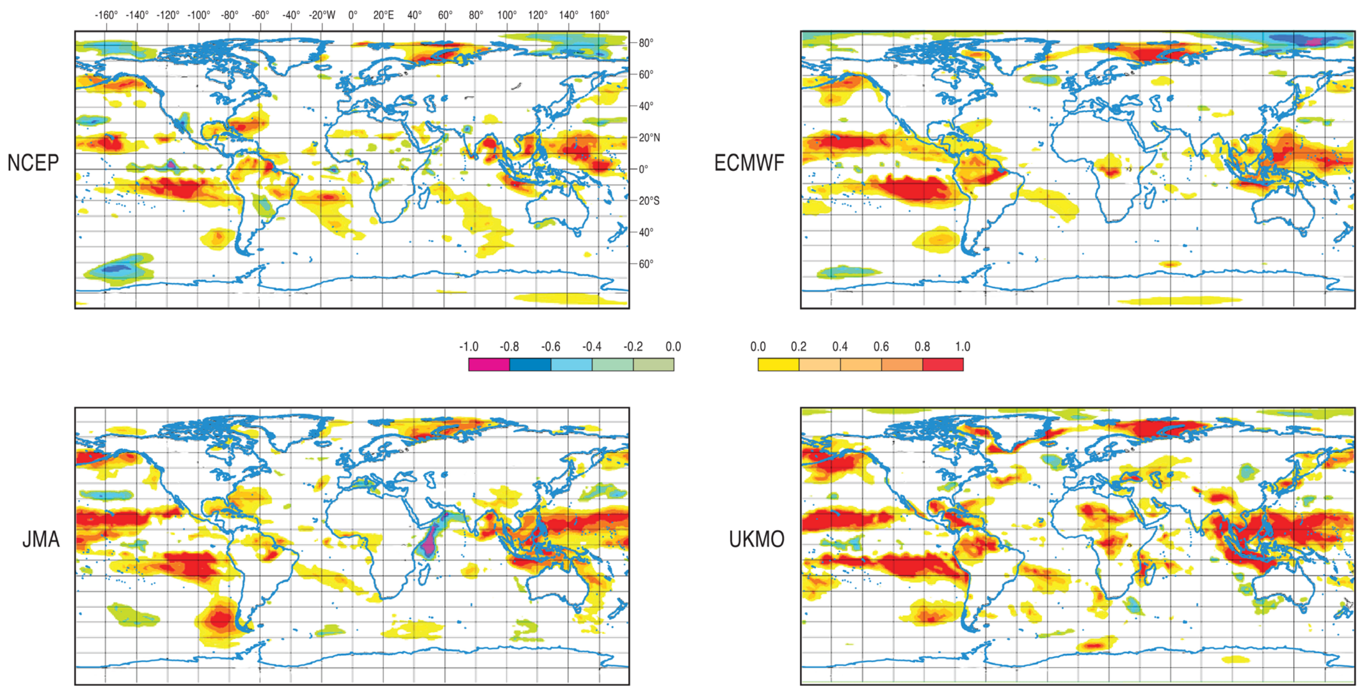


uate the skill of an extended range ensemble in predicting heat and cold waves is to use a selection of objective verification measures for probabilistic forecasts. In reality, verification requires a far larger sample than is available. This is typically the case for any investigation that involves extreme events. Here we show the evaluation of individual heat waves, as shown in Figure 3.30, as an example. The 2-metre temperature composites, based on weekly mean anomalies of ensembles forecasts at 12-18 days, are shown in Figure 3.31. Compared with the observations (Figure 3.30), the forecasts (Figure 3.31) generally identify the location of warm anomalies with a certain degree of accuracy, although the amplitude is underestimated. Overall, the successful predictions reflect a persistent anti-cyclonic circulation already present in the initial conditions. This testifies to the critical nature of an extended-range forecast model to represent transitions to anti-cyclonic circulation regimes, which is consistent with the cause of so-called medium-range forecast 'busts' (Rodwell et al., 2013).

Careful calibration and judicious combination of ensembles of forecasts from different models into a larger ensemble can give greater accuracy than is obtained from any single model. However, comparing, verifying and testing multimodel combinations from these forecasts and quantifying their uncertainty as well as the handling of such a massive dataset is challenging and is the subject of the ECMWF subseasonal to seasonal (S2S) prediction project. This is a WWRP/THORPEX-WCRP joint research project established to improve fore-

FIGURE 3.32

Extreme Forecast Index of 2-metre temperature with a forecast range of 12-18 days verifying the week of 8-14 August 2016. Four different forecast systems are shown. Blue areas indicate a cold spell, while red areas indicate a heat wave (on a weekly average). Ncep is National Centre for Environmental Prediction, ECMWF is the European Centre for Medium Range Weather Forecasting, JMA is Japan Meteorological Agency, UKMO is the United Kingdom Meteorological Office.
Source: courtesy of authors



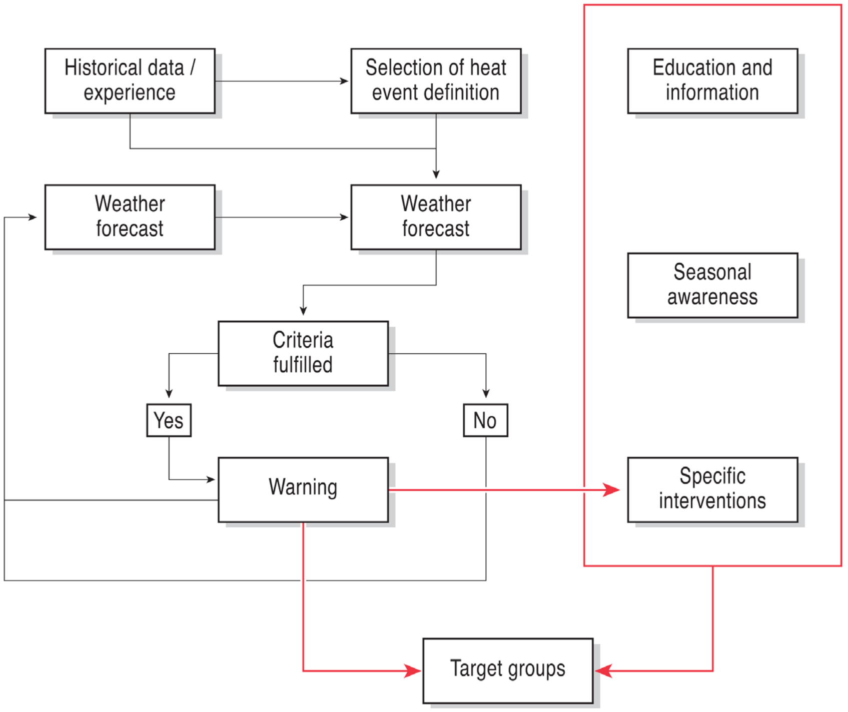
cast skill and understanding on the S2S timescale, and promote uptake of its forecast products by operational centres and the applications community. Examples of some of S2S's products can be found at ECMWF (n.d.). The Extreme Forecast Index (EFI) is one such product (Figure 3.32). This is an integral measure of the difference between the ensemble forecast distribution and the model climate distribution. The EFI takes values from –1 to +1. An EFI of 1 (red) indicates a heat wave, while an EFI of –1 (blue) shows a cold spell. Experience suggests that EFI magnitudes of 0.5-0.8 (irrespective of sign) can be generally regarded as signifying that 'unusual' weather is likely, while magnitudes above 0.8 usually signify that 'very unusual' or extreme weather is likely. Although larger EFI values indicate that an extreme event is more likely, the values do not represent probabilities as such.

3.8.6.2 Early warning systems

Early warning systems have been developed for a number of extreme climate events and are gaining traction in the area of temperature extremes (Carmona et al., 2016; Kalkstein et al., 2011; Kovats and Ebi, 2006; Lowe et al., 2016; McGregor et al., 2015). Such warning systems take the output from short- to medium-range forecasting models (Lowe et al., 2016; McGregor et al., 2006), such as described above, and usually use a threshold temperature or some related index to trigger an alert and/or issue a heat or cold warning (Antics et al., 2013; Nairn and Fawcett, 2015; Pascal et al., 2013). More often than not, a weather- or climate-based EWS for heat or cold, which is composed of a number of components, is nested within a wider heat or cold action plan (WHO, 2008, 2011; WMO, 2015) as shown in Figure 3.33.

FIGURE 3.33

**Generic structure of a heat health warning system. The components in the red box constitute part of a wider heat health action plan. This overall structure can also be applied to cold-related warning systems.
Source: McGregor et al. (2015)**



The normative view regarding heat/cold EWSs is that they should deliver discernible benefits for the management of heat- and cold-related risk across a range of sectors (Fouillet et al., 2008). Given this, heat/cold EWSs are increasingly subject to evaluation that can consider EWS processes and/or outcomes, using a variety of criteria. To date, such evaluations indicate that heat/cold EWSs yield discernible benefits in relation to DRM but, notwithstanding this, there is room for improvement, especially as a successful EWS depends heavily on a well-designed set of risk-mitigating and practical intervention strategies being in place (Bassil and Cole, 2010; Chiu et al., 2014; Ebi, 2007; Hajat et al., 2010; Kalkstein et al., 2011; Montero et al., 2010b; Toloo et al., 2013a, b).

For low-temperature extremes, a range of EWS and forecast products have been developed. Many of these are focused on forecasting snow storms (Nakai et al., 2012; Wang et al., 2013) and ice storms, with an emphasis on critical infrastructure such as roads (Berrocal et al., 2010; Degaetano et al., 2008; Palin et al., 2016; Riehm and Nordin, 2012) and power lines (Cerruti and Decker, 2012; Nygaard et al., 2015; Roldsgaard et al., 2015).

Although EWSs are considered a plausible DRM tool, developers and users of EWSs should be aware of some of the generic 'dos and don'ts' of such systems, as outlined by Glantz (2004).

3.8.6.3 Urban design and planning

Cities have received a great deal of attention in the DRM literature because this is where large numbers of people are concentrated; they are, therefore, potentially at risk of heat- and cold-related disasters.

In the case of heat, cities represent a distinct problem because of the so-called urban heat island (UHI) effect which, during periods of high temperatures, can lead to air temperatures in cities being several degrees above those for surrounding rural areas, especially during the nocturnal hours (Arnfield, 2003). This 'extra' heat has the potential to place a large number of vulnerable people in cities at risk of heat-related illness (Wolf and McGregor, 2013; Wolf et al., 2014).

The UHI develops because urban materials are efficient at absorbing and storing heat from the sun during the day and releasing that heat back into the urban atmosphere at night, leading to higher nocturnal temperatures in urban areas than in rural areas. A further factor is the low evaporation rates in cities; evaporation is an energy-consuming and thus a cooling process. Significant quantities of so-called anthropogenic heat from air conditioning systems and vehicles can add to the energy available for raising urban air temperatures (Allen et al., 2011; Offerle et al., 2005; Smith et al., 2009). For example, in London, it has been estimated that approximately 80 % of the anthropogenic heat goes into heating of the atmosphere (Iamarino et al., 2012), with the greatest contributions from London's central activity zone, where the service sector is predominant. Given that large cities, such as London, will grow over the coming decades, anthropogenic heat is likely to become an important heat risk management issue for large cities.

Managing temperature extremes can be approached from a number of perspectives, including using forecasting technology, the development of EWSs and heat/cold action plans and urban design and town planning.

Given the processes that generate the UHI, strategies that focus on managing urban heat can range from the scale of the individual building to the city. Examples include controlling for building material absorption and storage of energy from the sun, ensuring that evaporation is promoted through providing moist surfaces and developing green infrastructure and reducing anthropogenic heat release.

While the specific approaches to managing urban heat are potentially wide ranging (Alexander et al., 2016; Eliasson, 2000; Mills et al., 2010; Phelan et al., 2015), the degree of benefit (the intensity of cooling and improvements to human thermal comfort) arising from urban design- and city planning-related heat mitigation measures (Norton et al., 2015; Sharma et al., 2016; Sun et al., 2016;) depends on considering a multitude of interacting and potentially conflicting factors (Coutts et al., 2013; Hamilton et al., 2014). In addition to the scientific challenges (Chen et al., 2012), the actual mainstreaming of urban climate design and adaptation principles into city planning can sometimes become stalled because of a range of institutional barriers (Lenzholzer and Brown, 2011; Reckien et al., 2014; Ugolini et al., 2015; Uittenbroek et al., 2013; Wolf et al., 2015).

Relatively speaking, urban design for low-temperature extremes has received less attention in the recent DRM literature, no doubt as a result of a perception that, in the near future, heat, as opposed to cold, will pose a greater risk management problem. Interestingly, a consequence of the UHI effect, especially the role of anthropogenic heat, may bring some positive benefits in cities that experience harsh winter climates.

3.8.7 Conclusions and key messages

Partnerships

Cooperation between regional, national and international research communities and climate monitoring agencies and citizen scientists is required to construct internally consistent extreme temperature databases and meaningful sector-relevant extreme temperature metrics. This is particularly the case for urban environments where there is an ever-increasing concentration of people who are potentially at risk from temperature extremes as a result of the urban heat island (UHI) effect. A systematic approach at both national and local levels and across all sectors, involving state, private, voluntary and community actors, is required to understand the wider societal impacts of temperature extremes. Partnerships formed between stakeholders in the risk management of temperature extremes should adopt 'a communities of practice model' in order to develop integrated heat and cold action plans that transcend vulnerability assessment, weather forecasting, intervention strategies, urban design and city planning.

Knowledge

An enhanced understanding of the physical origins of temperature extremes, as well their changing magnitude and frequency, especially in light of climate change, is required. Where possible, historic non-instrument-based temperature records as captured in diaries and other documents could be used to augment the understanding of the climatology of temperature extremes from the local to the regional level. Long-term observational series need to be sustained through the commitment of resources to climate monitoring. Research should be undertaken to improve our understanding of the effectiveness and cost-effectiveness of extreme temperature-related interventions in a variety of different climatic, socioeconomic and cultural contexts, with learning shared widely. Conceptual risk models of complex disasters related to temperature extremes are required to scope out agendas for knowledge development.

Innovation

In the absence of observed weather station-based temperature data, the use of weather generators for the creation of temperature time series for extreme value analysis and alternative temperature observation platforms such as satellites in addition to the output from urban climate numerical models should be considered as input into DRM analyses. The idea of drawing on multiple sources of information from data networks, as encapsulated by the concept of 'the internet of things', offers considerable potential for managing disaster risk related to temperature extremes. High-resolution intra-urban mapping of population vulnerability to heat and cold, integrated with information on building type and air and surface temperature, is an innovation that is likely to yield gains for extreme temperature-related DRM.